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Turning the carbon supertanker: Sectoral feasibility of climate change mitigation in China

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ABSTRACT

Whether China can slow the growth of emissions of greenhouse gases and ultimately reduce them has become a central question for climate mitigation. In previous research on India, we developed a theoretical framework to assess the structural characteristics of different sectors and identify which ones were most amenable to mitigation. In this article, we extend that approach to China and review the nine sectors responsible for most of the country's emissions. These include electricity (disaggregating renewables, nuclear, and coal), road transportation, four disaggregated industry sub-sectors (steel, cement, fertilizers, and oil refining), and buildings. We identify two sets of attributes, what we called political/organizational feasibility and techno-economic feasibility, that together shape the possibilities for emissions mitigation. Our central intuition is that fragmentation – on the government or market side or both – makes collective action more difficult. Cement, steel, and oil refining possess favorable characteristics on both political/organizational feasibility and techno-economic feasibility, while fertilizers and renewables pose the most difficult challenges on both dimensions. Buildings and road transport are mixed cases, where techno-economic feasibility is high while political/organizational dynamics are more challenging. Finally, coal and nuclear are mixed cases where political/organizational feasibility is high but techno-economic aspects are more challenging.

1. Introduction

In the mid-2000s, China became the world's largest emitter of greenhouse gases (GHGs). By 2015, China's share of global CO_2 emissions was 29%, nearly double those of the second largest emitter, the United States [1]. In 2015, countries, including China, committed in Paris to an ambitious set of commitments to reduce global GHGs. While these Nationally Determined Contributions were voluntary, the inclusion of developed and developing countries in the Paris Agreement broke the logjam that had bedeviled previous efforts like the Kyoto Protocol. Whether China can restrain the growth and ultimately reduce its emissions of greenhouse gases has become one if not the central question for climate mitigation going forward. The 2016 election of Donald Trump to the presidency of the United States and his subsequent repudiation of the Paris Agreement has elevated China's importance to mitigation efforts.

China's Paris commitment included a peak in CO_2 emissions around 2030; a significant reduction of CO_2 emissions per unit of GDP; an increase in the share of non-fossil energy; and an increase in forest stock volume [2]. While concerns about air pollution and efforts to rebalance the economy have reinforced the country's resolve to address climate change and will deliver climate co-benefits, whether China is capable of achieving these goals is uncertain.

Reaching these targets has implications for different sectors of the Chinese economy. Previous research focused on technology options and economic feasibility [3,4]. However, efforts to reduce greenhouse gases also hinge on political and organizational attributes of the Chinese system. GHG mitigation requires collective action by both governmental and market actors. Sectors, however, possess different structural features that may facilitate or impede collective action. While preferences are important, abstracting from what actors want reveals attributes of systems that may make it hard to achieve objectives or potentially facilitate emissions mitigation.

In our previous research on India, we developed a theoretical framework to assess the structural characteristics of different sectors of the economy and identify which ones were most amenable to climate mitigation [5]. We noted that this framework helps answers a number of foundational questions including what kinds of political systems facilitate energy transitions, governance processes that produce optimal outcomes in the energy space, and reconciling challenges of energy security and environmental protection [6].

We identified two sets of attributes that we called *political/*

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organizational feasibility and *techno-economic feasibility*, which together shape the possibilities for emissions mitigation. The former captures the degree of fragmentation in governance and markets while the latter captures the scope for and cost of efficiency gains and emissions reductions in a sector. Some sectors possess favorable characteristics on both, some face unfavorable conditions, while others are mixed cases (favorable on one dimension and not the other).

Our primary contribution is on the political/organizational side, where we code the prospects for collective action by government actors and market actors separately and then together. For the *techno-economic feasibility* assessment, we mostly rely on existing studies to evaluate each sector's distance from the best available technology on the market and the costs of bringing that sector up to global efficiency standards. Our research is based on a review of policy documents, including Chinese language sources and about 18 interviews with government officials, academics, think tanks, and international donors that were carried out in Beijing in September 2016 (see Appendix F in the Supplementary file for an anonymized list). We sought to interview diverse sources, cover all the major sectors, and fill in details about the policy process that could not be answered with the existing literature or data. While more interviews would undoubtedly be welcome, we have been as thorough and comprehensive as possible, given available resources.

2. Collective action, governance in China, and sectoral emissions

Our central intuition is that fragmentation − either on the government or market side or both − makes collective action more difficult through higher transaction costs of organizing and developing a coherent approach [7–10]. On the government side, fragmentation is defined as situations where many government actors − namely more than two − possess rule-making authority in a given sector. Fragmentation can involve divisions between administrative departments in the central government and/or shared rule-making authority between the central government and provincial/local governments. On the market side, fragmentation, as we operationalize below, reflects many market actors being responsible for production and emissions in a sector.

While this observation about the impediments to collective action from large groups is not new, we offer a synthetic account of the combination of political and market structures on the prospects for emissions mitigation. Collective action may still be possible in the face of either market or government fragmentation, but it will be more challenging and costly. Structurally, where one side is fragmented, collective action may be possible when the power distribution favors the concentrated side, what Stirling calls "asymmetric agency" [11].

Previous landmark studies of the policy process in China from the reform period of the late 1980s evoked the notion of "fragmented authoritarianism." Models of fragmented authoritarianism captured the diffusion of power away from the central state to provincial and local governments and private actors in a country still governed by a non-democratic system [12]. This approach depicted the "functional division of authority among various bureaucracies to produce a situation in which it is often necessary to achieve agreement among an array of bodies, where no single body has authority over the others" [13].

As Elizabeth Economy argued, fragmentation made collective action on the environment more challenging as local authorities faced contradictory signals from the central government and often privileged economic growth [14]. However, contemporary scholarship has suggested re-centralization of policy has occurred in some domains, motivated by the need for economic rebalancing and to control corruption [15]. The center's effort to claw back authority has seen stronger impetus under the leadership of President Xi. Recent studies suggest sectoral variation in re-centralization. While the Chinese state retains control over top-tier sectors such as state-owned enterprises in heavy industry, the state leaves more room for local and private sector actors in the middle-tiers (such as steel, automobiles, and alternative energy) and bottom-tiers (such as personal services) [16,pp.32–35].

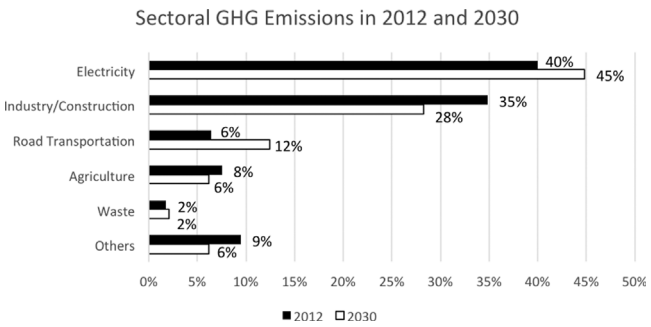

Fig. 1. Sector-wise breakdown of contributions to GHG emissions in China.
Source: 2012 data comes from CAIT; 2030 data comes from McKinsey & Company.

These observations suggest a single model of fragmentation or centralization is inadequate to capture the complexity of Chinese governance. We provide an empirically grounded and theoretically informed assessment of sectoral variation in governance in China. We include the nine most important sectors responsible for most of the country's emissions, both now and projected. The sectors include electricity (disaggregating coal, renewables, and nuclear), road transportation, four disaggregated industry sub-sectors (steel, cement, fertilizers, and oil refining), and buildings. These sectors were responsible for more than 70% of total GHG emissions in China in 2005 and their share of GHG emissions will increase to about 85% in 2030 [17] (see Fig. 1[1] and Appendix Table A1 in the Supplementary file for industry sub-sectors). While buildings is a demand-side sub-sector, it is an important sector in its own right, both as a source of direct emissions of GHGs as well as indirect emissions from its use of electricity.

Three sectors − cement, steel, and oil refining − possess favorable characteristics in terms of political/organizational and techno-economic feasibility. We find that fertilizers and renewables pose the most difficult challenge on both dimensions, though a determined Chinese state may be able to overcome these obstacles through government reorganization. Buildings and road transport are mixed cases, where techno-economic feasibility is high while political/organizational dynamics are more challenging. Finally, coal and nuclear are mixed cases where political/organizational feasibility is high but techno-economic aspects are more challenging (see Fig. 7's sectoral coding and Appendix E's in the Supplementary file disaggregated breakdown for each sub-dimension).

3. Coding rules

Our argument is based on political/organizational and techno-economic feasibility. Each has two sub-dimensions where we code high or low feasibility. This yields an overall two-by-two matrix and two nested sub-matrices. Fig. 2 displays our overall feasibility coding. Cell A shows hard cases where feasibility is low on both dimensions. Cell C includes the most feasible cases, where feasibility is high on both dimensions. Cells B and D are mixed cases that possess high feasibility on one dimension and low on another. Cell B has low political/organizational feasibility but high techno-economic feasibility while Cell D has low techno-economic feasibility but high political/organizational feasibility.

[1] We combined some sub-categories in order to match the 2030 data.

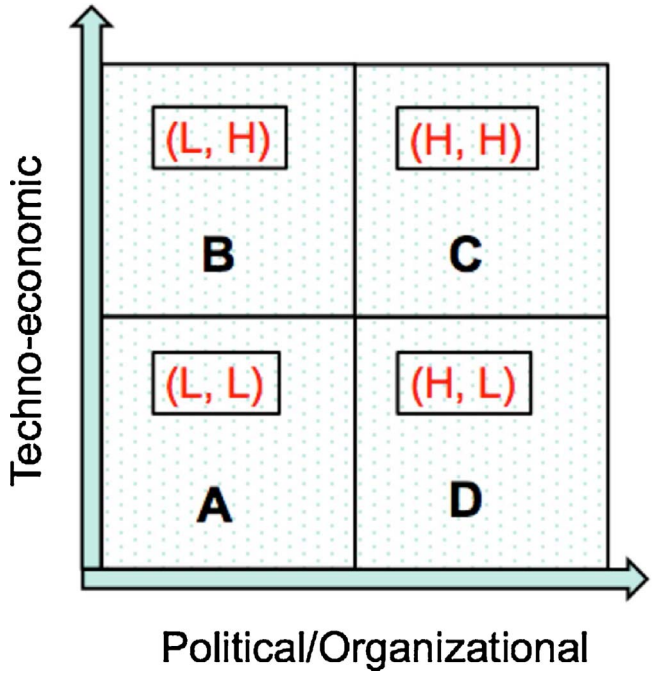

Fig. 2. Overall Assessment of Mitigation Feasibility.

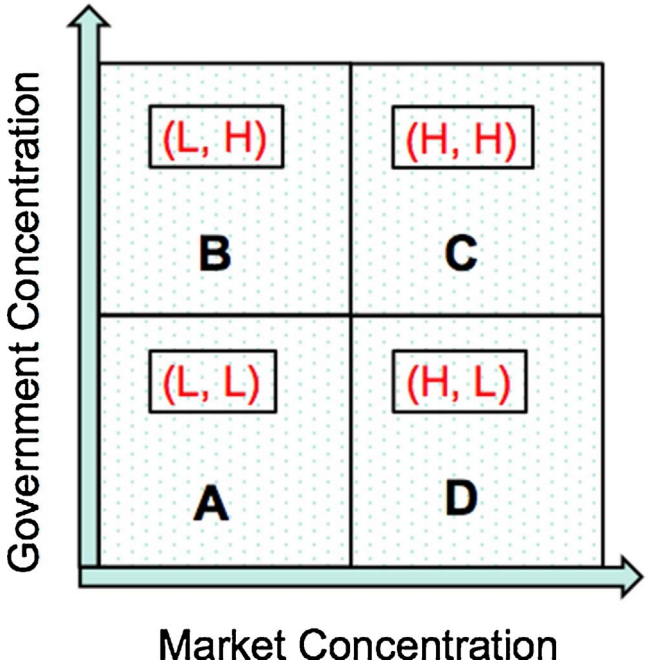

Fig. 3. Political/Organizational Feasibility.

3.1. Political/organizational feasibility

Going further, we unpack political and organizational feasibility which includes two dimensions:, *the degree of market concentration* and *the degree of government concentration.* On the market side, when there are many market actors, changes in behavior by any one of them has limited impact on the overall market. By contrast, in concentrated markets, changes by any one firm will radiate through the entire market. We capture concentration by looking at the market share of the top four producers (known as CR4), using the convention that a CR4 of 50% or more constitutes a concentrated market (we occasionally report other CR or market share values). Moreover, where markets are segmented regionally, changes in one region will not extend nationally [18].

Concentrated markets facilitate collective action. That said, market concentration can confer political power so if market actors oppose climate mitigation, they may be able to capture or bend policy to their wishes. Concentrated markets are not inherently opposed to climate mitigation. Self-regulation by major firms is possible, particularly when leading companies are globally integrated and face pressures to conform to world standards [19,20]. In China, many firms are state-owned enterprises (SOEs); though they are subject to state regulation, they may have independent interests. Because they are responsible for production and emissions, we count them as market actors.

Government concentration reflects situations where rule-making is primarily carried out by the national government. Fragmentation leads to policy contestation between national and local actors or among national actors, undermining coherent policy action and change. Following the logic of veto players theory, fragmentation favors inertia [21]. Since implementation almost always is carried out by sub-national actors, we focus on rule-making processes. One can observe government fragmentation when there are multiple national level agencies that have overlapping authority over rule-making in a given sector and/or when provinces are also involved in rule-making.

One of the challenges of coding concentration is the tendency of the Chinese government through organs such as the State Council to establish high-level policy guidance that an agency like the National Development and Reform Commission (NDRC) then translates into more specific targets for particular provinces [15]. That target-setting is not simply imposed on provinces, but is often negotiated, providing an opportunity for provinces to shift policies in more favorable directions [22,23]. We tend to code a sector as concentrated with respect to government when there are few nodes of rule-making authority. We operationalize concentrated rule-making authority as two or fewer government actors.

We distinguish concentration from power, following Stirling, defined as asymmetric agency to affect outcomes [11]. As we show in Fig. 3, where governments are concentrated but markets are fragmented (Cell B), emissions mitigation is possible when governments possess asymmetric power to impose solutions on market actors. We test for power through demonstrated outcomes or behavior. We code instances where governments possess asymmetric power as high political/organizational feasibility. By the same token, where governments are fragmented but markets are concentrated (Cell D), we code cases as high feasibility if markets actors possess asymmetric power, recognizing that whether markets actors avail themselves of this option depends on their preferences.

The least likely cases for successful mitigation are ones where both government and markets are fragmented (Cell A). When markets and government are both concentrated (Cell C), that on some level facilitates collective action, but it can also lead to clashes if power is relatively balanced and where there is a history of government-market actor conflict. We code such cases as high feasibility if there is a consensual history between them and one side possesses a clear power advantage. While subnational action may be possible in fragmented systems, we are interested in collective action at the national level.

3.2. Techno-economic feasibility

In terms of techno-economic feasibility, we compare each sector to the *best available technologies (BAT)* globally that are available. We include alternative technologies that are already commercially available that would allow a sector to leapfrog beyond current sectoral efficiencies, especially relevant in the electricity space. To the extent that

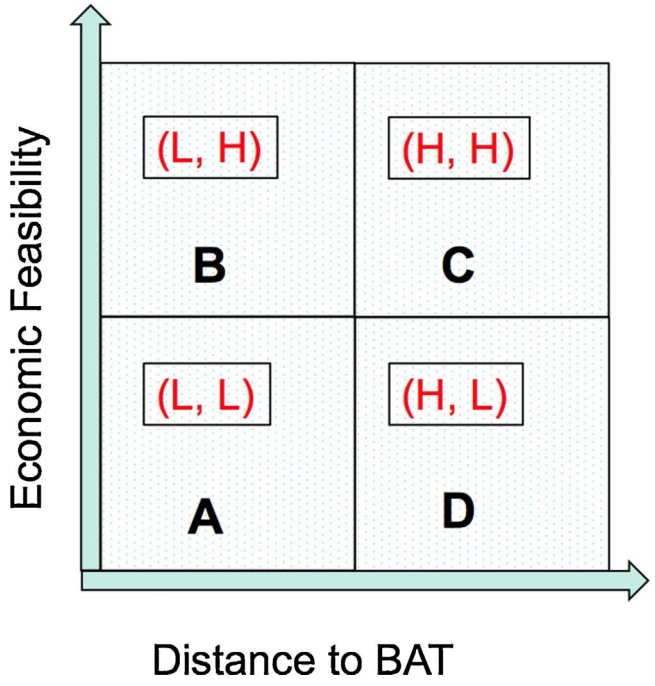

Fig. 4. Techno-Economic Feasibility.

most of a sector is near BAT, there is little room for further emissions mitigation. That is, there is low technological feasibility. The second dimension we consider is *costs*. As we show in Fig. 4, where the sector is below BAT, and the adjustment costs of are low, these are best case scenarios, possessing both high technological and high economic feasibility (Cell C). Where the sector is near BAT and the costs of adjustment are high, these are cases of low techno-economic feasibility (Cell A). Where the sector is below BAT, but costs are high (i.e. low economic feasibility), these are mixed cases that we code as low (mix) (Cell D). Finally, where the sector is near BAT, but the costs of bringing it to global standards are low in Cell B, there is high economic feasibility but limited room for further efficiency gains. We rate these cases as somewhat favorable and capture such cases by locating them near the horizontal line between high and low techno-economic feasibility in Fig. 2.

In the following sections, we code all sectors on each dimension of feasibility. We conclude by placing each sector in our overall typology as well as each nested one (see Figs. 5–7).

4. Electricity

The electricity sector accounted for about 40% of GHG emissions in China in 2012 [17]. Projections show the sector will likely account for about 45% of GHG emissions in 2030 [3]. The large and likely increasing share of GHG emissions illustrate the electricity sector's importance.

Thermal power is the largest source of Chinese electricity generation, which accounted for about 75.43% of total electricity generation in 2014. Coal contributed about 93.46% of total thermal power generation in 2014, and gas only about 3.15%. The second largest source of Chinese electricity generation is hydropower, which accounted for about 18.91% of total electricity generation in 2014 but whose prospects for further growth are limited. Wind power, nuclear, and solar power accounted for about 2.85% 2.38%, and 0.42% in 2014, respectively [24]. Although the application of renewable energy is increasing rapidly in China, coal will likely dominate electricity generation in China until 2030 [25]. Therefore, we concentrate on coal, but will also discuss renewables and nuclear, as they have the largest growth potential.

4.1. Political/Organizational feasibility

Most Chinese power plants belong to five power generation groups (central government SOEs),[2] seven SOEs and fifteen provincial government-owned or local government-owned power generation enterprises. Appendices A3 and A4 in the Supplementary file list their installed capacity and power generation in 2014. The total installed capacity in China was 1360 GW in 2014, with central government, and provincial and local government ownership being respectively 61% and 10% of the total, the remainder in private hands [24].

The CR4 of installed capacity of thermal power, hydropower, nuclear power, and wind power are 42%, 36%, 100%, and 52%, respectively based on each company's installed capacity and power generation (see Appendix A2 in the Supplementary file).[3] Thus the market concentration of nuclear power is very high while the market concentration of thermal power, hydropower, and wind power is low.

Three SOEs − the State Grid Corporation of China (SGCC), China Southern Power Grid (CSG), and Inner Mongolia Power (Group) Co. Ltd − dominate the electricity market for transmission and distribution. These three state-owned enterprises sold and distributed 81% of all electricity power in China in 2014.[4]

Inter-regional power transfer is mainly planned and managed by the central government. The degree to which inter-regional (inter-provincial) transactions of energy are subject to market forces is low. Some provincial governments even directly intervene in transactions between provinces and regions [26]. In 2014, inter-regional power transfer only accounted for 15 percent of total power generation [24].

The electricity market includes diverse energy resources, a fragmented generation market, and a concentrated distribution market, and it is divided into regional markets, so we assess market concentration as low. Though such highly regionalized markets give electricity the characteristics of a local monopoly, it will count as fragmented, since we are evaluating potential for national mitigation.

Before 2013, electricity regulation was dispersed among at least 15 departments [27]. In order to integrate fragmented government regulation and reduce overlapping responsibilities, the National Energy Commission and State Electricity Regulatory Commission were merged into the National Energy Administration (NEA) in 2013. NEA is directly managed by NDRC. Since then, the key policy-making agencies in the central government are NDRC and NEA, and they are responsible for designing the general guidance of electricity sector development. Several other departments under NDRC also regulate the electricity sector, such as the Department of Price and Department of Climate Change. Regulation responsibilities of the electricity sector are also distributed among other ministries or departments, including the Ministry of Industry and Information Technology (MIIT), Ministry of Science and Technology (MOST), Ministry of Environmental Protection (MEP), and Ministry of Land and Resources (MOLR). The regulatory roles among these administrations or departments are sometimes overlapping and unclear to some extent [28,29] (interview #4).

However, the task of phasing out and upgrading outdated capacity of coal-fired power plants is centralized. It was the main focus of the landmark first meeting of National Energy Commission in 2014, whose chair was the head of the State Council, and the sixth meeting of The Leading Group for Financial and Economic Affairs in 2014. In the central government these tasks are mainly regulated by NDRC, NEA, MEP, and MIIT. During the 12th five year plan (2011–2016), 28 GW coal-fired units were phased out, exceeding the target of 20 GW. The

[2] Five power generation groups include China Datang Corporation, China Guodian Corporation, China Huadian Group, China Huaneng Group, and China Power Investment Corporation. These five groups are among the world's 500 largest companies (Fortune Global 500).

[3] These are authors' calculations based on annual reports.

[4] Authors' calculations based on each company's annual report or social responsibility report.

central government decomposed the national target of energy-saving and backward capacity-cutting to provinces and central government-owned enterprises. Although the approval authority of coal-fired thermal power projects has been delegated to provinces, any approval must be in accordance with national electricity development plans [30]. In the face of overcapacity, the central government released four documents in 2016 restricting new coal-fired power plants and phasing out backward capacity, with penalties for any violations. Furthermore, the central government has established strict regulations on coal consumption.

Thus, rule-making authority in the coal power sector lies predominantly with the central government, with direction from high-level entities like the National Energy Commission. Therefore, we assess government concentration as **high**. Though market concentration is **low,** the central government is more powerful than the market, as evidenced by its record of shutting down a large number of coal plants, many controlled by provincial governments. Thus the political/organizational feasibility of the coal sector is judged to be **high**.

Government concentration in the nuclear power sector is also **high**. Any nuclear project investment must obtain approval from State Council [30]. Furthermore, government has relatively high control on this sector and maintains a power asymmetry over the three SOEs, which hews closer to the top-tier of commanding heights given the potential for dual use of nuclear technology. As market concentration in nuclear power is also **high**, we rate overall political/organizational feasibility of nuclear power as **high**.

In the renewables sector, provincial and local governments have a higher degree of autonomy. Planning by the central government and provincial governments is not always consistent. Provincial and local governments consider local resources and economic development as well as national level concerns such as emissions mitigation. For example, in July 2016, NEA released the planning for a unified electricity market in the Jing-Jin-Ji area (including He Bei province), but in August 2016, He Bei province released its own plan to build a separate market for the north of the province. There has been contested rule-making in other areas. For example, NEA sets the minimum operation hours for wind power and solar power. However, Gan Su province in 2016 released a provincial policy with much lower operating hours for both. While Gan Su subsequently delayed implementation of its alternative rules, provincial participation in rule-making raises questions about policy coherence [31,32] (interviews #1 and #4). Therefore, **low** market and government concentration characterize the renewables sector, and political/organizational feasibility is assessed to be **low.**

4.2. Techno-economic feasibility

Since 2005, China sought to lower energy consumption by building many low coal-consumption power units (namely supercritical and ultra-supercritical units). As a result, the net and gross coal consumption rates for coal-fired power plants have decreased (see Appendix A5 in the Supplementary file).[5] The gross and net coal consumption rates for fossil fuel fired power plants above 600 MW in 2014 were 319 gce/kW and 300 gce/kW, respectively. By contrast, the gross and net coal consumption rates for coal-fired power plants in Japan were 305 gce/kWh and 294 gce/kWh, respectively. The average efficiency of coal-fired power generation units in major coal-using countries varies enormously, from 30% to 45% [33]. By comparison, the average design efficiency of 600 megawatt (MW) coal-fired power units in China was 48.18% in 2014, meaning large coal plants are near BAT [34]. However, the number of operating hours of coal-fired power plants in China is low (operation h in 2015 were only 3969, the lowest since 1978, which means that actual efficiency is lower than the designed efficiency).[6]

Moreover, China still has many smaller inefficient plants, including 5782 units below 300 MW (see Appendix A6 in the Supplementary file). China started to develop supercritical (SC) and ultra-supercritical (USC) units in 1992, but the commercial operation of SC and USC only began in 2003. Since 2010, coal-fired power plants with a unit-size equal or above 600 MW started to use SC and USC [35]. The share of SC, USC and subcritical units in a benchmarking contest in 2013 shows that the current share of SC and USC in China is between 50% and 65% (see Appendix A7 in the Supplementary file) (interviews #2 and #12). This positions the power sector well short of BAT.

One potential way to further improve energy efficiency and reduce GHG emissions is to phase out outdated coal-fired power units that cannot meet retrofitting conditions. While many old plants have already been retired, the 13th five-year power plan says that by 2020, about 20 GW in additional capacity should be phased out. The costs of phasing out outdated coal-fired power units and capacity include costs of employee resettlement, subsidies for power plants, and incentives, which usually are high.

Another strategy to reduce emissions and improve efficiency would be to elevate more of China's coal fleet to USC.[7] While this would be more emissions intensive than renewables, it represents the best available technology in the coal sector, with other technologies like carbon capture and sequestration and integrated gasification combined cycle largely still in the demonstration phase. One scenario analysis that included various cleaner coal technologies estimated that the costs for increasing USC technologies alone in China would be in the high range of $US582bn to $US655bn by 2030 [35]. The IEA and Nuclear Energy Agency estimated that levelized costs of ultra-supercritical units is about $74/MWh in 2015 in China, which is much more expensive than hydro, nuclear, solar PV, and wind [36].

The third and most aggressive mitigation approach is to replace coal-fired power plants with low carbon energy. We focus on renewables and nuclear since they have the largest growth potential. Compared to coal power, wind and solar energy generation are expensive. In 2014, power generation costs of coal-fired power plants were about 0.2 yuan/kWh, while generation costs of wind energy and solar energy were at least 0.5 yuan/KWh and 0.8 yuan/kWh, respectively (not considering environmental costs) [37,38]. While a bit dated, McKinsey estimated the costs to achieve 183 GW installation of nuclear, 150 GW installation of wind and 30 GW installation of solar by 2030. In their estimation, total costs were about $2.1 billion, $4 billion, and $6 billion, and the costs of reducing 1 ton CO_2 by installing nuclear, wind, solar and IGCC were $4.5, $23, $26, and $46, respectively [39]. McKinsey concluded that the abatement costs in the electricity sector were among the highest of all carbon-intensive sectors. In 2015, IEA and Nuclear Energy Agency estimated the levelized costs of electricity for generating plants in China. The results showed that nuclear power, though still expensive, was much cheaper ($25/MWh-$30/MWh), compared to rooftop solar PV ($59/MWh), ground-mounted solar PV ($55/MWh), and wind ($46/MWh–$52/MWh) [36].

Furthermore, although China has a large number of renewable energy installations, most capacity is installed in remote areas; thus, to promote local use of renewable energy, long-distance *trans*-regional transmission capacity is needed. The costs of extending the grid to remote areas and ultra-high-voltage transmission are particularly high. The cost of building 1 km ultra-high-voltage (UHV) electricity transmission line is about $1.4 million [39]. Across these different strategies in the electricity sector − shutting down aging coal plants, elevating the coal sector to USC, and replacing coal-fired power with low carbon

[5] The net coal consumption rate is the average coal consumption for generating 1 kWh power; the gross coal consumption rate is the average coal consumption for providing 1 kWh power, including both power generation and power transmission.

[6] Between 5000–6000 h of operation per year is considered desirable in China.

[7] Efficiencies can be gained on the margins by modest retrofits to existing sub-critical plants and by converting more facilities to combined heat and power (CHP).

energy, our judgment is that the costs are high (**low** economic feasibility). Though the sector is below BAT (**high** technical feasibility), our overall judgment for electricity is **low (mix)** techno-economic feasibility.

In conclusion, our overall judgment is that coal and nuclear are cases of **mixed** feasibility (high political/organizational but low techno-economic feasibility), and renewables is characterized by **low** feasibility (low on both political/organizational and techno-economic grounds).

5. Industry

Direct emissions from industry accounted for 35% of GHG emissions in China in 2012 [17], the second largest contributor of GHG emissions. The three biggest industry contributors are steel, cement, and chemicals, accounting for about 74% of manufacturing emissions in 2012 [40]. Therefore, we focus on GHG mitigation in those sub-sectors.

5.1. Steel

China's steel industry is energy-intensive. CO_2 emissions of the steel industry accounted for about 35% of total CO_2 emissions in manufacturing in 2012 [41]. Total coal consumption of the steel industry was about 655 million tons in 2015, which accounted for about 15% of China's total coal consumption.

5.1.1. Political/Organizational feasibility

There are about 500 steel enterprises, and more than 400 are privately-owned (see Appendix B1 in the Supplementary file for the number of steel plants). Among these privately-owned enterprises, only 7 have production capacity above 10 million tons; more than 200 steel enterprises have production capacity below 1 million tons [42]. The CR4 of pig iron, crude steel, and steel products are 21%, 20%, and 15%, respectively (see Appendices B2–B4 in the Supplementary file). We conclude that the market concentration for the steel industry in China is **low**.

The central government is the main actor involved in energy-saving and carbon-reduction of the steel sector, mainly regulated by the Ministry of Industry and Information Technology (MIIT). MIIT is responsible for shutting down inefficient capacity and technology upgrading, but the Department of Resource Conservation and Environment Protection under NDRC regulates steel sector energy conservation and carbon reduction goals. Government regulations mainly focus on setting standards and helping the steel industry cut overcapacity, primarily through targets. The central government sets a national target and decomposes it to provinces and central government-owned enterprises that in turn allocate them to cities and enterprises. These targets are "rigid constraints" for provincial governments and steel enterprises (interview #10). If provincial governments cannot achieve their targets, the central government may stop approving state investment projects. If enterprises cannot achieve their overcapacity-cutting targets, relevant agencies are not allowed to issue any administrative licenses, such as land-use and new investments [43].

During the 11th five-year plan period (2006–2010), 122.7 million tons of iron-making capacity and 72.2 million tons of steel-making capacity were phased out [44]. During the 12th five-year plan period (2011–2016), 90.9 million tons of iron-making capacity and 94.9 million tons of steel-making capacity were phased out [45]. In 2016, the Central Economic Work Conference listed "cutting overcapacity" as the most important task and steel as a key sector. In 2016, the national target to cut overcapacity in the steel industry was 45 million tons of steel, about 6% of steel production in 2015.

While progress in the first half of 2016 was slow and enterprises and provinces were reluctant to shut down steel plants, the central government has relatively high control in cutting overcapacity. Although the sector's approval authority has been decentralized to provincial governments, the central government released policy guidance strengthening enforcement to prohibit new steel capacity. Since August 2016, the State Council sent several inspection groups (Du Cha Zu) to provinces and cities, in order to achieve the remaining annual target for 2016. Pressure from the central government sped up the process of cutting overcapacity. By the end of September 2016, 80% of the overcapacity-cutting target had been accomplished [46].

NDRC and MIIT are the main agencies involved in regulation. The central government's ability to prevail in achieving targets in spite of provincial resistance indicates its asymmetric agency. On some level, steel sector liberalization reflects Pearson's argument that it is a middle-tier sector [16]. However, the central government's efforts to shut down excess capacity as part of wider economic rebalancing and environmental goals suggests the state retains authority. Therefore, we assess government concentration as **high**.

Recalling that market concentration is **low,** and that the government is more influential than the market, we assess political/organizational feasibility as **high.**

5.1.2. Techno-economic feasibility

Energy efficiency of China's steel industry has improved but has not reached BAT (see Appendices B5 and B6 in the Supplementary file). The average energy consumption in the sintering process, blast furnace ironmaking process, the conversion to steel process, and crude steel products are 49.2 kgce/t, 398 kgce/t, −7.04 kgce/t, and 592 kgce/t, while advanced energy consumption values (the current lowest energy consumption values) of these processes are 40 kgce/t, 377 kgce/t, −22 kgce/t, and 540 kgce/t, respectively [47,48].

The big problem is the technology polarization between large enterprises and small steel companies. Large enterprises have achieved advanced emission standards, but many small companies use outdated technologies. 30% of iron making blast furnaces in China are less than 999 cubic meters, and 34% of steelmaking equipment has production capacity less than 100 tons, which is generally inefficient and far behind BAT (see Appendices B7 and B8 in the Supplementary file).

While some technologies in the steel sector are somewhat costly, many are not. Some available technologies, such as coke dry quenching technology, coal moisture control technology, all-burned blast furnace gas boilers, and low calorific value combined cycle gas power generation have negative marginal costs and high CO_2 reduction potential (see Appendix B9 in the Supplementary file). The marginal costs per ton CO_2 of all these technologies in Appendix B9 in the Supplementary file are negative, ranging from −254 Yuan/tCO_2 to −1086 Yuan/tCO_2. If China could apply these thirteen technologies to 800 million tons of steel production, the total CO_2 reduction potential is 287.6 MT CO_2, about 18% of the sector's emissions in 2012. Nevertheless, some observers believe the main barrier to producing high-quality steel is high costs (interview #10). For example, the social costs of shutting down steel plants are high. The vice-president of China Steel and Iron Association pointed out that cutting overcapacity will involve about 500,000 employees in steel industries [49].

Overall, the Chinese steel industry has not achieved BAT, indicating **high** technical feasibility. Although some technologies in the steel industry have high costs, the costs of others are low, and substantial mitigation gains can still be made by deploying these technologies. Therefore, we assess the techno-economic feasibility in the steel sector as **high**. Since political/organizational feasibility is high, we code the sector's overall feasibility as **high**.

5.2. Cement

China is the world's largest cement producer, and production increased from 0.6 billion tons in 2000 to 2.3 billion tons in 2015. In 2014, China accounted for 59% of global cement production, followed by India (7%), and the United States (2%) [50]. The cement industry's CO_2 emissions were 1063 Mt in 2010, and the Energy Research Institute

projects CO_2 emissions of the cement industry will increase to 1323 Mt in 2020 [4].

5.2.1. Political/Organizational feasibility

In 2013, there were 3840 cement manufacturing firms in China [51]. Cement enterprises are widely distributed in eastern, central, and western China (see Appendix B11 in the Supplementary file). Private firms account for about 75% of enterprises, but their market share is small (see Appendix B12 in the Supplementary file). The CR4 of the cement industry was 36% (see Appendix B10 in the Supplementary file for CR4 to CR50) [51]. There are eight SOEs among the top 10 cement manufacturers. These eight largest SOEs accounted for 45% of production capacity in China in 2013. Besides cement manufacturing, 6672 firms produce concrete and cement products [51]. There were 1398 production line cement clinker firms in 2011, and their average production capacity was 3,098t/d (see Appendix B13 in the Supplementary file) [52]. 59% of production lines had a production capacity per day higher than 4,000t/d in 2011. Taking into account both the market structure and the number of production lines, we assess the cement market in China as fragmented.

The cement industry is mainly regulated by the Ministry of Housing and Urban-Rural Development (MHURD) and the Ministry of Industry and Information Technology (MIIT). That said, the cement sector has been liberalized in recent years, and the Cement Industry Association plays an important role bridging the market and the government (interview #11).

The main role of the central government in the cement industry is to set standards and help reduce overcapacity. Provincial and local governments (the local department of industry and information technology) are in charge of supervision and implementation of industry standards. Implementation is uneven across provinces (interview #11). For example, if limestone is the only resource in a local area, the local government will complain about national policy or even resist cuts in capacity [53,54]. The fragmented market structure of the cement industry complicates efforts to cut overcapacity. Although the industry is only using 60% of its capacity [53], cement enterprises do not want to exit the market.

Like steel, another middle-tier sector, the central government still dominates rule-making for capacity and has tried to strengthen enforcement [16]. The Chinese government has made great progress in cutting cement overcapacity since 2010. 49.7 million tons of capacity was phased out in 2015, and 776.3 million tons of capacity has been phased out since 2010. Although approval for new investments in cement were decentralized to provincial governments since 2014 [30], the central government requires all provincial governments, local governments, and relevant departments to strictly implement the "The Guidance of Solving Serious Overcapacity Problem (2013)" from the State Council when approving new investments. In May 2016, the State Council released additional policy guidance that prohibited additional capacity before 2020. New capacity cannot obtain administrative licenses. The guidance also urged provincial governments to reduce overcapacity in the cement industry and increase CR10 of the cement sector to 60% by 2020 [55].

Strong policy signals from the central government are effective in accelerating local action. After announcement of the "Guidance," all the provinces released their specific plans to cut cement overcapacity, control production, increase market concentration, and upgrade technologies during the 13th Five Year Plan (2016–2020).

Plant shutdowns are a key component of climate mitigation, and rule-making for this resides with the central government. Thus, while market concentration is **low**, government concentration in cement is assessed to be **high**. Additionally, despite liberalization, the central government also has a record of achieving plant shutdown goals, demonstrating asymmetric agency. Therefore, we assess political/organizational feasibility of the cement industry as **high**.

5.2.2. Techno-economic feasibility

The Chinese government sets clear standards for energy conservation and energy efficiency in the cement industry. The comprehensive energy consumption of cement has decreased 23% in the last decade (see Fig. B1 in the Supplementary file). The 12th five-year plan of energy saving and emissions reduction regulates that energy consumption of cement clinker should decrease from 134kgce/t to 112 kgce/t and 37 billion tons of overcapacity of cement should be closed down. However, the advanced value of comprehensive energy consumption (the current lowest energy consumption values) is below 103 kgce/t. Additionally, the share of alternative fuels in the cement sector in China is less than 10% while several European countries have achieved 50% [56]. Therefore, the cement industry has not achieved BAT.

According to a report from the Natural Resources Defense Council (NRDC), increasing the percentage of alternative fuel is an achievable BAT for the Chinese cement industry, especially by using industrial waste residue [57]. Use of combustible waste in cement kilns as an alternative fuel is another possibility. Although the technology itself is cost-efficient, diffusion of these technologies needs relevant policies and coordination among different ministries [57]. The Energy and Environment Economic Research Institute from Tsinghua University estimated the costs of eighteen potential technologies to reduce energy consumption in the cement sector [58]. Thirteen technologies had negative costs, ranging from -108 Yuan/t CO_2 to -1522 Yuan/t CO_2 (see Appendix B14 in the Supplementary file). The CO_2 reduction potential ranges from 1.32 kg CO_2/t cement to 86.67 kg CO_2/t cement. Therefore, the costs of reducing emissions in the cement sector are low.

In conclusion, the Chinese cement industry has not achieved BAT (**high** technical feasibility), and the costs of several best available technologies that can save energy and reduce emissions are low (**high** economic feasibility). Thus we assess the techno-economic feasibility of the cement sector as **high**. Since political/organizational feasibility is high, we code overall feasibility as **high**.

5.3. Petroleum and chemicals

The petroleum and chemical industry is an energy-intensive industry, which includes more than 50 important sub-sectors (i.e. oil and gas exploitation, basic chemicals, fertilizers, and pesticides) and more than 60,000 products [59]. CO_2 emissions in the petroleum and chemical industry accounted for about 25% of total CO_2 emissions in China in 2015, which will increase to 28% in 2020 [4]. Two of the most energy-intensive and emission-intensive sub-sectors are oil refining and fertilizers. Ammonia is the chemical with the largest CO_2 emissions, accounting for 27% of emissions in the chemical industry in 2007 [60]. About 80% of ammonia is used in producing fertilizer [61]. Another important sector is oil refining. The CO_2 emissions of oil refining in 2010 were 152 million tons [62]. We discuss fertilizers and oil refining separately.

5.3.1. Fertilizers

5.3.1.1. Political/Organizational feasibility. In 2014, there were 1848 fertilizer firms in China, widely distributed around the country [63]. The CR4 of the fertilizer sector is about 25%.[8] Urea is the key sub-sector that contributes the most to GHG emissions. There are seven SOEs owned by different levels of government in the urea sector. The CR10 of the urea sub-sector is 49%, mean CR4 is well below 50%. The CR21 of the nitrogenous fertilizer sub-sector is 69%. Therefore the market concentration in fertilizers is low. Local protection (from provincial governments and local governments) and administrative barriers often occur in the fertilizer industry [63], which can partially explain low market concentration.

The fertilizer sector is relatively liberalized. In August 2014, the

[8] Compiled from the financial reports of the top 6 fertilizer producers.

State Council cancelled the need for government approval of fertilizer investment projects, which means that decision-making of new investments in fertilizer projects belongs to market actors. The central government mainly uses value-added taxes, export tariffs, electricity prices, transportation fees, and environmental regulation to regulate the fertilizer industry [64]. In the central government, the fertilizer industry is regulated by the NDRC, Ministry of Industry and Information Technology (MIIT), General Administration of Quality Supervision, Inspection and Quarantine (GAQSIQ), Ministry of Science and Technology (MST), and Ministry of Agriculture (MA). NDRC mainly focuses on overall development of the industry, while MIIT and MST mainly focus on technology innovation and industry standards and GAQSIQ and MA on quality supervision [65]. Provincial and local governments are allowed to provide favorable electricity prices and land to support local fertilizer enterprises, though these must be in accordance with national policy. With some overlapping responsibilities among executive agencies and the absence of a clear hierarchical authority, we code this sector as fragmented.

As a result, we regarded overall government concentration in the fertilizer sector as **low**. With government and market concentration both low, we assess the political/organizational feasibility of fertilizers as **low**.

5.3.1.2. Techno-economic feasibility. The large-scale equipment used to produce nitrogenous fertilizer in China has achieved world levels in advanced technologies, such as water-coal slurry gasification and entrained flow coal gasification [66]. Still, in 2014, the energy consumption to produce large-scale synthesis ammonia was about 24.7% higher than world-level advanced technologies [61]. In the nitrogenous fertilizer sector, there are many medium- and small-scale firms with energy consumption at least 30% to 50% higher than world-level advanced technologies [61]. Therefore, we conclude that technologies in the fertilizer sector are behind BAT.

From the perspective of energy sources, coal accounted for about 76% of total fertilizer production, while the proportion of natural gas, which has a lower GHG footprint than coal, in producing synthesis ammonia was only about 22% in 2014 [67]. If China could increase the share of natural gas by 20%, CO_2 emissions could be reduced by 16% [57]. The equipment costs of using natural gas as raw materials are cheaper than using coal, but natural gas is more expensive than coal, and the net effect of this is higher transition costs. Moreover, in the process of liberalization, the government cancelled several policies for the fertilizer industry such as favorable rail transportation and natural gas prices. As a result, the financial health of fertilizer enterprises is relatively weak [67].

In conclusion, the fertilizer industry in China has not achieved BAT (**high** technical feasibility), but the costs of technology upgrades are high (**low** economic feasibility). So we assess techno-economic feasibility in the fertilizer industry as **low (mix).** Given low political/organizational feasibility, our overall evaluation is that fertilizers is a hard case for emissions reduction (**low** feasibility). While declining natural gas prices might ease techno-economic feasibility, progress in this sector would require (1) either industry consolidation and pressures to conform to global standards or (2) efforts by government to reassert and clarify central rule-making authority.

5.3.2. Oil refining

5.3.2.1. Political/organizational feasibility. The China National Petroleum Corporation (CNPC) and China Petroleum & Chemical Corporation (Sinopec) are the two major market actors. In 2014, those two SOEs accounted for approximately three-quarters of gasoline, diesel, and crude oil production, respectively [68,69]. Seven SOEs account for about 79.3% of total crude oil processing capacity; regional and private oil refineries account for the rest [70] (see Appendix B15 in the Supplementary file). Thus, the oil refining market is concentrated.

The central government is the major actor in regulating oil refining, with the major regulators including NDRC, NEA under NDRC, Ministry of Industry and Information Technology (MIIT), Ministry of Finance (MF), State Administration of Taxation (SAT), General Administration of Quality Supervision (AQSIQ), and Ministry of Environmental protection (MEP). Approval of new and expansion of existing oil refining projects are regulated by the State Council. The pricing mechanism of refined oil products is controlled by NDRC. Consumption taxes of refined oil products are regulated by MF and SAT. Emissions standards for the oil refining sector are set by MEP and AQSIQ. The restriction of energy consumption per unit is regulated by NDRC, AQSIQ, and Standardization Administration of China. The five-year plan for petroleum and chemical industry is instituted by MIIT. These ministries have overlapping responsibility for regulating oil refining. For example, seven ministries are involved in improvement of refined oil quality,[9] including NDRC, MF, MEP, MC, State Administration of Industry and Commerce (SAIC), SAIC, and NEA. These ministries also have conflicts regulating oil refining (interview #13).

In conclusion, the market concentration of the oil refining sector is **high**; government concentration is however **low**. As SOEs, two major market actors CNPC and Sinopec are the dominant actors in this space with more power than government agencies (interview #13). This is an interesting case in terms of Pearson's discussion of tiers, petroleum being a top-tier sector dominated by two SOEs. Structurally, what matters is the market is concentrated and the power balance favors market actors, enabling major mitigation actions should the firms decide to do so. Therefore, our overall assessment of political/organizational feasibility is **high**. Climate mitigation advocates could try to convince Sinopec and CNPC to enact ambitious climate mitigation goals to make progress in the oil refining sector.

5.3.2.2. Techno-economic feasibility. Although overcapacity is a problem in the oil refining sector, advanced production capacity is insufficient in China. The oil refining sector has not achieved BAT in terms of energy efficiency. Average comprehensive energy consumption in the oil refining industry is about 60.61 kg standard oil/ton crude oil, but comprehensive energy consumption in oil refineries in technologically advanced countries is less than 40 kg standard oil/ton crude oil. The average yield of light oil is about 78.01% in China, but the level in technologically advanced countries is about 85% (see Appendix B16 in the Supplementary file). Comparing Chinese oil refineries and other countries shows that Chinese refineries have a much smaller average annual production (see Appendix B17 in the Supplementary file). The distribution of refineries' production shows that inefficient capacity still accounts for a large share (see Appendix B18 in the Supplementary file). There is thus large potential for energy efficiency improvements in the Chinese oil refining industry.

In 2013, MIIT released guidance on emissions reductions and energy saving in the petrochemical and chemical industry, and identified six technology directions: combined heat among equipment and hot delivery technology, ultrasonic cleaning technology, secondary condenser technology, plate cooling technology, refinery wastewater high efficient treatment technology and membrane separation hydrogen recovery technology [71].

McKinsey identified five technologies relevant to refining, and estimated the abatement costs and CO_2 reduction potentials. Energy efficiency from behavioral changes, improved maintenance and process control, among other measures have negative abatement costs, ranging from −$85 to −$50 per t CO_2e. Co-generation has relatively high abatement costs, ranging from $10 to $55 per t CO_2e [72].

NDRC in 2015 estimated the costs of several energy-saving and low-

[9] Improvement of refined oil quality involves technology upgrading of oil refiners, improvement of energy consumption indices, and phase out of outdated production capacity.

carbon technologies for oil refining such as petrochemical enterprise energy balance and optimal operation technology, heat recovery technology, ultrasonic cleaning technology, as well as several others. Based on several assumptions, the costs range from $112 million to $3.7 billion. Based on typical cases for each technology in the report, payback periods for all these technologies are at most three years, so we assess that the costs are achievable. The aggregate CO_2 reduction potential across all the technologies was about 25 MT/a, about 14% of CO_2 emissions in the sector in 2015 [73].

Therefore, the sector is below BAT (**high** technical feasibility), and we judge the costs to be low (**high** economic feasibility). Our judgment therefore is **high** techno-economic feasibility and **high** overall feasibility.

6. Transportation

CO_2 emissions in the transportation sector increased from 327 Mt in 2000 to 701 Mt in 2010 in China, and CO_2 intensity of transportation also increased from 0.26 tCO_2 in 2000 to 0.53 tCO_2 in 2010 [41]. United Nations projections show that CO_2 emissions will increase to 1065 Mt in 2020 and CO_2 intensity will increase to 0.76 t CO_2. Road transportation accounts for about 76% of cargo carrying capacity and about 86% of passenger carrying capacity in China; thus, we focus on road transportation, though recognize China has made major strides to encourage intra- and inter-city rail [74].

Rapid growth in vehicle ownership in China is an important reason for increased transportation emissions. In the last decade, ownership increased by about 365%, to about 172 million vehicles in 2015 (See Fig. C1 in the Supplementary file).

6.1. Political/organizational feasibility

The vehicle market in China is dominated by domestic producers (including joint ventures). Imported vehicles only account for about 5% of total sales. The CR4 of vehicle producers (not including motorcycles) is 62% (see Appendix C1 in the Supplementary file). The market structure shows the vehicle market is concentrated. The six largest groups among all the vehicle producers are all SOEs, three of which belong to the central government and three to local governments. The market structure of truck producers is also concentrated. The CR4 of heavy trucks is 70% and the largest six groups are SOEs; the CR4 of heavy-sized trucks is 70%, medium-sized trucks 77%, light trucks 66%, and micro trucks 88% (see Appendices C2–C5 in the Supplementary file). We have found evidence that changes in fuel efficiency in the transportation sector also frequently involve improvements in fuel quality, implicating the oil refinery sector. Though that makes the sector somewhat more fragmented, we nonetheless assess that the market concentration of road transportation as **high**.

Nine ministries directly regulate the automobile industry [75]. The climate change department under NDRC is responsible for decomposing the national target to the transportation sector. Specific policies are designed and implemented by the environmental protection agency of the comprehensive planning department under the Ministry of Transportation. The Ministry of Transportation also provides special funds to support energy-saving and emissions reduction projects. These 9 relevant ministries have conflicting interests and different policy objectives, which makes vehicle producers sometimes feel confused about policies [75] (interview #9). For example, ten ministries are involved in oil quality improvement. The multi-management system in the transportation department leads to difficulties in developing a unified and coherent policy. Also, regional protectionism exists in the automobile industry. Because the industry is an important source of revenue, provincial and local governments often offer many favorable policies to attract automobile investors.

Therefore government concentration is assessed as **low**. Given that the market structure of vehicle producers is **high** and the government is fragmented **(low** government concentration), the relative power balance between the two becomes relevant. Compared to market actors, the government is relatively strong in carrying out regulations in transportation (interview #9). The government controls the production, investment, new plant construction and mergers of automobile producers. Enterprises have to obtain the approval and registration from government departments. With the state retaining asymmetric agency but fragmented, it makes developing a coherent position difficult. We therefore assess the political/organizational feasibility of the transportation sector as **low**. The prospects for successful national action hinge on either liberalization of the sector to favor industry (and encourage self-regulation to global standards) or centralization of state authority with a clearer hierarchy of ministries in charge of regulating standards related to automobile fuels and vehicle efficiency.

6.2. Techno-economic feasibility

Comparing China to the U.S., Japan, and the EU's average fuel economy of new vehicles shows a gap between China's technology and BAT (see Appendix C6 in the Supplementary file). As traffic congestion is serious in almost all the large cities in China and vehicle producers' fuel economy claims could be inaccurate, actual fuel consumption is 70% higher than designed fuel consumption (interview #9).

Nonetheless, there are four potential technology approaches to reduce oil consumption and GHG emissions (see Appendix C7 in the Supplementary file). The first approach is to improve fuel economy, including homogeneous charge compression ignition for both diesel vehicles and gasoline vehicles (HCCI); gasoline direct injection (GDI); and high efficiency diesel cars, gasoline trucks, and diesel trucks. As costs can be offset by fuel saving, marginal costs of these technologies are negative, ranging from −2641.5 Yuan to −1114.1 Yuan. The other three directions are to develop hybrid electric vehicles, pure electric vehicles, and alternative fuels. The costs of these technologies are high. There is also the option of supporting public transit.

In order to mitigate GHG emissions associated with road transportation and improve air quality, the Chinese government has, in addition to fostering mass transit, emphasized the development of new energy vehicles and improved fuel economy. By 2020, the fuel economy of passenger vehicles and advanced vehicles are to reach 56 mpg and 63 mpg respectively, with the goal for commercial vehicles to approach fuel economy of advanced industrialized countries [76].

In conclusion, China's transportation sector has not reached BAT (**high** technical feasibility). The options with the largest emissions reductions potential − homogenous charge compression ignition, high efficiency gasoline trucks, and support for public transit − all have net negative costs so we assess transport as having **high** economic feasibility. Therefore, we assess the techno-economic feasibility as **high**. Given low political/organizational feasibility, our overall assessment for transportation is **mixed**.

7. Buildings

In 2010, total CO_2 emissions of the building sector were 1447 Mt, including direct emissions from fuel burning on site as well as indirect emissions from electricity drawn from the grid [4]. That was about 16% of the country's CO_2 emissions in 2010 [1]. Heating in northern urban areas, urban residences, public buildings, and rural residences were responsible for 29%, 23%, 26%, and 21% of total CO_2 emissions in the sector, respectively [4]. Projections show that total CO_2 emissions will increase to 2120 Mt in 2020 and 3300 Mt in 2050 [4,77]. From 2000–2012, China's average residential floor area per person (including urban and rural residential) increased from less than 20 m^2 per person to nearly 32 m^2 per person [78]. Space heating is the largest end-use energy consumption, which accounts for about 32% of all energy consumption; lighting, space cooling, and appliances are the second, which account for 30%; water heating 20% and cooking 14% [79].

7.1. Political/organizational feasibility

In 2013, the number of real estate developers in China was 91,444 [74]. The market share of real estate developers with a first-level qualification certificate is about 10%.[10] There are about 4–8 real estate enterprises with first-level qualification certificate in each city, which means CR4 is less than 10% [80]. Therefore, we conclude that the real estate market is fragmented.

Energy saving and GHG mitigation in buildings is mainly governed by the central government, but provincial and local governments also issue their own standards. Several ministries are involved in energy-saving and GHG mitigation regulation, including NDRC, Ministry of Housing and Urban-Rural Development (MHURD), Ministry of Finance (MF), State Administration of Taxation (SAT), Ministry of Science and Technology (MST), Ministry of Environmental Protection (MEP) and General Administration of Quality Supervision, Inspection and Quarantine. General energy-saving and emission reduction policies and building codes (i.e., building design standards and construction standards) are designed by NDRC and MHURD. Existing building retrofitting is governed by MHURD. NDRC and NEA regulate district heating. MIIT regulates energy-saving of appliances. MF and SAT are involved in special government funds for building retrofitting and heat metering reformation.

Based on the central government's building special plans (zhuan xiang gui hua), provincial and local governments also issue their own building codes, special funds, and relevant regulations. As energy-saving in the building sector would increase real estate costs, provincial and local governments do not have strong incentives to improve efficiency and building codes [81]. Furthermore, building retrofitting needs a lot of capital input. As a result, GHG mitigation regulation in buildings is uneven across provinces. Only 15 provinces (or cities or districts) have their own regional building energy-saving law, and only 11 have local laws about materials for walls [82]. Among more than 130 cities with heating provisions, only 40 issued heating metering reforms [83].

The regulation of energy intensive buildings in China started in 2006, so is relatively new. The government does not have very effective ways to enforce and monitor the implementation of energy-saving and emission-reduction policies in buildings. In particular, local governments lack techniques to test building materials or monitor construction [82]. In the face of complicated construction, agencies have unclear responsibilities, and they lack coordination [84].

Therefore, taking into account existing authorities in each level of government, the government structure is fragmented. As both market and government concentrations are **low** in the building sector, we assess political/organizational feasibility of the building sector as **low**.

7.2. Techno-economic feasibility

In China, the total area of floor space that is energy efficient is only 10 billion square meters (interview #8), meaning about 84% of buildings are inefficient. For residential buildings, energy-saving buildings account for about 30% of the total. Inefficient buildings tend to have single pane windows, no insulation, and high air leakage [85]. Although codes of pilot buildings in China are comparable to those in the EU, building codes generally are far behind. Because of poor insulation, the heat loss of Chinese buildings is high, about 15% to 30% [86]. Therefore, Chinese building codes need large improvements.

Heating in northern urban areas is responsible for 29% of total CO_2 emissions in China in the buildings sector. Northern China is heated largely by district heating systems (concentrated heating). The energy consumption of heating is about 130 million tce, accounting for about 10% of total energy consumption in China and for more than 50% of total energy consumption in the buildings sector in northern China. But heating technology in China is behind BAT. Average energy consumption of heating in China is more than two times the average energy consumption of heating in developed counties with similar climate conditions [78].

There are several available technologies for heating, urban residences, rural residences, and public buildings (see Appendix D1 in the Supplementary file). For heating, cogeneration and industrial waste-heat recovery are cost-effective (negative costs). For residences, high efficiency appliances, including solar water heaters, washing machines, refrigerators, tablet computers, retrofits of incandescent lamps, and heat pipe air conditioners, are cost-effective. Other policies, such as building retrofits, however, are expensive [85].

Building technologies in China are behind BAT (**high** technical feasibility). Although the costs of achieving some BATs are high, there are still many available low-cost technologies (**high** economic feasibility). Therefore, we assess techno-economic feasibility as **high**. Given low political/organizational feasibility, our overall evaluation of the sector is **mixed**.

8. Sectoral summary and conclusions

We summarize our conclusions from the various sectors in a series of diagrams. In the first, we map the sectors in terms of political and organizational feasibility. In the second, we do the same for techno-economic feasibility. The third and final typology brings these dimensions together, showing our overall sectoral coding, which includes a disaggregated evaluation in the electricity sector (separating coal, nuclear, and renewables). We notionally map the cases both in different cells but also directionally within the cells relative to other sectors, recognizing their precise placement is a judgment call based on the available evidence.

In terms of political/organizational feasibility, Fig. 5 shows three hard cases in cell A − buildings, renewables, and fertilizers − where both markets and government are fragmented. Four cases are located in cell B, characterized by government concentration but market fragmentation, including steel, coal, cement, and fertilizers. In all but fertilizers the government possesses asymmetric agency. We also observe two cases in cell D − oil refining and road transportation − of market concentration and government fragmentation. In oil refining, the government does not have clear asymmetric power over the two SOEs, which creates a favorable dynamic for self-regulation if the companies seize the opportunity. In road transportation, the government still possesses a power differential over manufacturers, but because it is fragmented, the government has difficulty forging a coherent policy. We code the case as marginally low political/organizational feasibility. Nuclear is the only sub-sector with both government and market concentration.

In terms of techno-economic feasibility, none of the sectors is near BAT so all possess high technological feasibility. However, as Fig. 6 shows, two cases − electricity and fertilizers − have high costs, making them more challenging economically for emissions mitigation. The other cases face manageable costs, and we believe the hierarchy of economic feasibility from most to least is cement, steel, oil refining, road transportation, and then buildings.

Together, our overall feasibility assessment in Fig. 7 suggests cement, steel, and oil refining are the most favorable cases for emissions mitigation (cell C), where they are high on both dimensions. Both coal and nuclear have high political/organizational feasibility but low techno-economic feasibility due to high costs (cell D). Buildings and transport face lower political/organizational feasibility but high techno-economic feasibility (cell B). Road transport is an area, like the coal sector, where government re-organization to concentrate authority or differentiate responsibilities among agencies might lead to more

[10] The first-level qualification is the highest certificate in the building sector. The market share of real estate enterprises with first level qualification is an average value of 32 large cities in China.

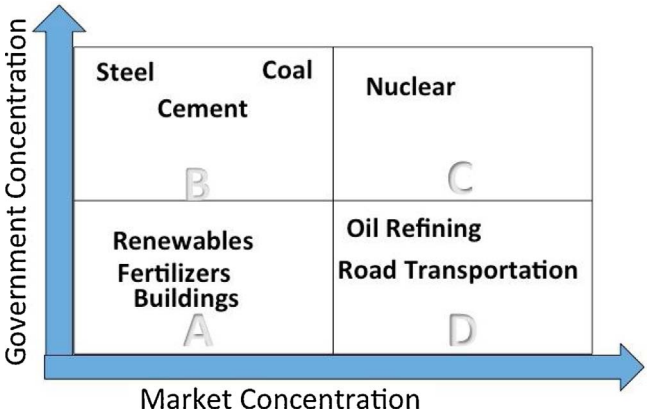

Fig. 5. Coding of China's Sectors for Political/Organizational Feasibility.

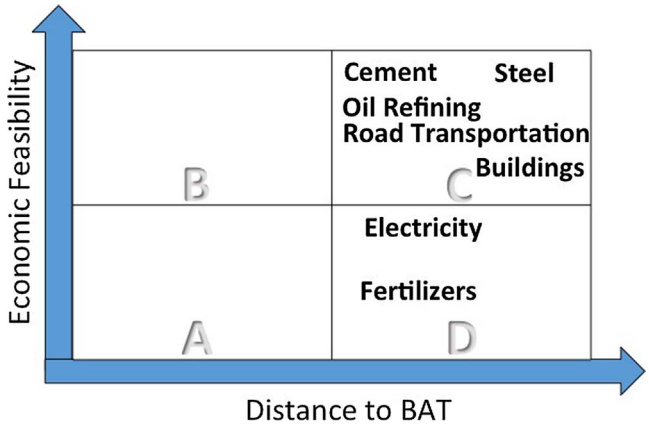

Fig. 6. Coding of China's Sectors for Techno-economic Feasibility.

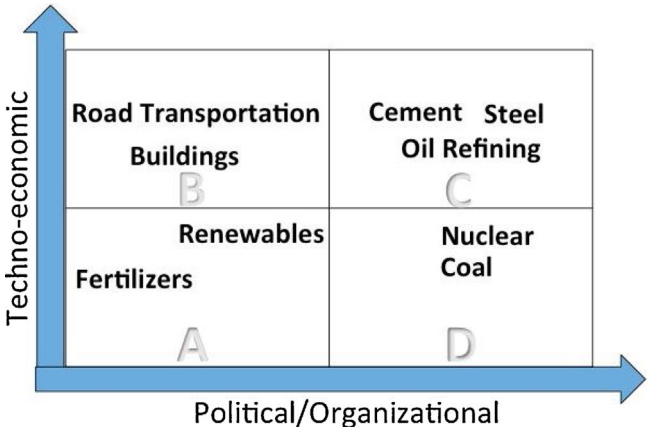

Fig. 7. Coding of China's Sectors for Overall Emissions Mitigation Feasibility.

coherent national level action. We judge fertilizers to be a difficult case in cell A.

One sub-sector – renewables – faces fragmented markets and governance and expensive transition costs. This sector is different than all others save nuclear in that it needs to grow rather than reduce emissions or shut down dirty plants. Efforts to boost renewables in China may yet succeed, but the effort will be challenging and expensive, given the barriers of fragmentation and cost. With air quality problems persistent, the announcement in early 2017 of plans to spend $360 billion on renewables over five years is both a testament to the government's resolve and the difficulties of scaling up renewables [87].

What then do our findings say about the nature of policy process in the Chinese system? Our results largely support the conclusions from Chen and Naughton that the Chinese central state has retained its prerogatives in the country's strategic direction [15, p. 6]. This accords with what Naughton and Tsai call "state capitalism" where "The state retains direct control of strategic sectors, engages in industrial policy, and holds a dominant position in the banking sector and equity markets" [88, p. 3]. At the same time, we continue to observe, per Pearson's observation, that some middle-tier sectors such as renewables and buildings permit more fragmentation [16].

What this means is that, if our coding of the cases is right, there is some sectoral variation in the scope for collective action. While the Chinese state possesses asymmetric power and government concentration in several sectors (namely cement, steel, coal, and nuclear), top-down collective action is possible in the oil refining sector if the two main state-owned companies self-regulate. In more fragmented sectors such as renewables, buildings, and fertilizers, central government directives and even industry self-regulation will likely face difficult challenges of implementation at scale. To facilitate action in sectors less amenable to collective action, China can re-centralize authority and/or seek to provide the government with a clear power asymmetry. This might be a strategy for fertilizers and road transport, for example. In newer sectors like renewables, market processes may in time generate more industry concentration, and a strategy of premature centralization might foreclose a period of innovation and consolidation. A committed Chinese state may be able to overcome some of these obstacles at great cost if highly motivated for other reasons, such as part of economic rebalancing, air pollution control, or to address corruption. Whatever specific solutions China embraces, we believe anticipation of the barriers to collective action, informed by analysis like ours, would likely be salutary for sectoral emissions mitigation strategy going forward.

We plan on pursuing related themes in future research. In on-going research on India, we are examining whether concentration, either on the government or market side, is helpful or necessary for scale-up in a new sector where there are fewer incumbent firms and government policy is going through rapid learning. In China's solar space, which has been oriented around exports, industry consolidation is occurring as many firms faced overleveraged debt positions and are closing or are being bought out by better resourced and connected firms [89]. Whether India will face the efflorescence of many firms and later rationalization remains to be seen.

Finally, having separate papers on China and India allows for comparisons. India is an established federal democracy with a legacy of a strong bureaucracy, while China is an authoritarian system where the central government has retained and expanded its authority. While both face severe air quality problems, China is more industrialized but also richer and able to invest in climate mitigation goals. We aim to deepen this analysis in subsequent work. To be sure, these problems and challenges are not going away any time soon.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.erss.2017.09.003.

References

[1] Global Carbon Project, Carbon Budget 2016, (2016) [Online]. Available: http://www.globalcarbonproject.org/carbonbudget/16/presentation.htm . (Accessed: 06 January 2017).
[2] UNFCCC, China's INDC – Enhanced Actions on Climate Change, Jun-. [Online], (2015) Available: http://www4.unfccc.int/Submissions/INDC/Published%20Documents/China/1/China's%20INDC%20-%20on%2030%20June%202015.pdf.
[3] McKinsey and Company, China's Green Revolution, (2009) [Online]. Available: http://www.mckinsey.com/clientservice/ccsi/pdf/china_green_revolution.pdf.
[4] 戴彦德, 胡秀莲, and others, 中国二氧化碳减排技术潜力和成本研究 (Potential

and Cost Study on China's Carbon Mitigation Technologies), 1st ed. 中国环境出版社, 2013.
[5] J.W. Busby, S. Shidore, When decarbonization meets development: the sectoral feasibility of greenhouse gas mitigation in India, Energy Res. Soc. Sci. 23 (2017) 60–73.
[6] B.K. Sovacool, What are we doing here? Analyzing fifteen years of energy scholarship and proposing a social science research agenda, Energy Res. Soc. Sci. 1 (2014) 1–29.
[7] K.A. Oye, Cooperation Under Anarchy, Princeton University Press, Princeton, N.J, 1986.
[8] M. Olson, The Logic of Collective Action: Public Goods and the Theory of Groups, Harvard University Press, Cambridge, 1965.
[9] E.B. Weiss, H. Jacobsen, Engaging Countries Strengthening Compliance with International Environmental Accords, (1998) Cambridge, MA.
[10] D.D. Murphy, The Structure of Regulatory Competition, Oxford University Press, Oxford, 2004.
[11] A. Stirling, Transforming power: social science and the politics of energy choices, Energy Res. Soc. Sci. 1 (2014) 83–95.
[12] K.G. Lieberthal, M. Oksenberg, Policy Making in China: Leaders, Structures, and Processes, Princeton University Press, Princeton, 1988.
[13] Bureaucracy, in: K.G. Lieberthal, D.M. Lampton (Eds.), Politics, and Decision Making in Post-Mao China, University of California Press, Berkeley, 1992.
[14] E. Economy, The River Runs Black: The Environmental Challenge to China's Future, Cornell University Press, Ithaca, 2004.
[15] L. Chen, B. Naughton, An institutionalized policy-making mechanism: China's return to techno-industrial policy, Res. Policy 45 (December (10)) (2016) 2138–2152.
[16] M.M. Pearson, State-Owned business and party-state regulation in China's modern political economy, in: K. Naughton, K. Tsai (Eds.), State Capitalism, Institutional Adaptation, and the Chinese Miracle, Cambridge University Press, Cambridge, 2015, pp. 27–45.
[17] World Resources Institute, CAIT 2.0: WRI's Climate Data Explorer, (2015).
[18] E.B. Kapstein, J.W. Busby, Social movements and market transformations: lessons from HIV/AIDS and climate change, Int. Stud. Q. 60 (2) (2016) 317–329.
[19] D.P. Baron, Business and Its Environment, 7th ed., Pearson, Boston, 2013 [Online]. Available: http://cait.wri.org/wri.
[20] J.F. Green, Rethinking Private Authority: Agents and Entrepreneurs in Global Environmental Governance, (2013) Princeton.
[21] G. Tsebelis, Veto Players: How Political Institutions Work, Russell Sage Foundation, New York, 2002.
[22] H. Li, X. Zhao, Y. Yu, T. Wu, Y. Qi, China's numerical management system for reducing national energy intensity, Energy Policy 94 (Jul. 2016) 64–76.
[23] D. Guttman, Y. Song, Making central-local relations work: comparing America and China environmental governance systems, Front. Environ. Sci. Eng. China 1 (4) (2007) 418–433.
[24] 电力统计年鉴 Electricity Industry Statistics, China Electricity Council, 2014.
[25] S. Bakewell, China Power Seen Doubling With Renewables as Coal Holds Sway, Bloomberg.com, 2013 [Online]. Available: https://www.bloomberg.com/news/articles/2013-08-27/china-power-seen-doubling-with-renewables-as-coal-holds-sway . (Accessed: 18 January 2017).
[26] 年全国电力调度交易与市场秩序监管报告," 国家能源局, 2016.
[27] 程宇婕 and 于欢, "能源改革再聚焦：箭在弦上 择机而动（聚焦两会·2013）" 中国能源报, (04 March 2013).
[28] 丁芸 and 林韵, "能源管理部门之间的协调性分析——以新能源发电行业为例" 首都经济贸易大学学报 1, 45–49, 2014.
[29] 电力监管权力配置研究--《西南政法大学》2014 年博士论文.
[30] 国务院关于发布政府核准的投资项目目录(2014 年本)的通知 Circular of the State Council on Promulgating the Catalogue of Investment Projects Subject to the Approval of the Government (2014 Version), State Council, 2014.
[31] 关于做好风电、光伏发电全额保障性收购管理工作的通知 (Notice on the Management of the Protection of the Purchase of Wind Power and Photovoltaic Power Generation), National Development and Reform Commission, and National Energy Administration, 2016.
[32] 关于下达 2016 年优先发电计划的通知 (Notice on Priorities of Electricity Generation Plan in 2016), Commission of Industry and Information Technology of GanSu Province, 2016.
[33] IEA, Technology Roadmap: High-Efficiency, Low-Emissions Coal-Fired Power Generation, (2012) [Online]. Available: https://www.iea.org/publications/freepublications/publication/technology-roadmap-high-efficiency-low-emissions-coal-fired-power-generation.html . (Accessed: 04 January 2017).
[34] 中国能源统计年鉴 China energy statistical yearbook, National Bureau of Statistics of China, 2014.
[35] C. Na, J. Yuan, Y. Xu, Z. Hu, Penetration of clean coal technology and its impact on China's power industry, Energy Strategy Rev. 7 (2015) 1–8.
[36] O. IEA, Nuclear Energy Agency, Projected Costs of Generating Electricity －2015 Edition, Int. Energy Agency Nucl. Energy Agency Fr., 2015.
[37] X. Ouyang, B. Lin, Levelized cost of electricity (LCOE) of renewable energies and required subsidies in China, Energy Policy 70 (2014) 64–73.
[38] 聂襲, 吕涛, "考虑环境成本的燃煤发电与光伏发电成本比较研究" *中国人口· 资源与环境*, no. 2015 年 11, 88–94, 2015.
[39] China Green Revolution, McKinsey & Company, 2009.
[40] 齐晔, *中国低碳发展报告* (2011–2012). 社会科学文献出版社, 2012.
[41] Y. Qi, Annual Review of Low-Carbon Development in China (2011–2012), (2011).
[42] C. Na, J. Yuan, Y. Xu, Z. Hu, Penetration of clean coal technology and its impact on China's power industry, Energy Strategy Rev. 7 (2015) 1–8.
董鹏, 杨亮, and 郑元彬, "'钢铁去产能须走出'囚徒困境.'" 中国矿业报 July 19, 2016. Available at: http://www.mlr.gov.cn/xwdt/jrxw/201607/t20160719_1411904.htm.
[43] 关于印发淘汰落后产能工作考核实施方案的通知 Circular of the State Council on the Appraisal Implementation Plan for the Work of Eliminating Backward Production Capacity, Ministry of Industry and Information Technology of the People's Republic of China, 2011.
[44] 钢铁工业'十二五'发展规划," 中华人民共和国工业和信息化部, 2011.
[45] 钢铁工业调整升级规划 2016–2020 Adjustment and Upgrade Plan of Iron and Steel Industry (2016–2020), Ministry of Industry and Information Technology of the People's Republic of China, 2016.
[46] 于祥明, "煤钢去产能提速 已完成全年目标逾八成--财经--人民网," 人民网, 15 October 2016. [Online]. Available: http://finance.people.com.cn/n1/2016/1015/c1004-28780974.html. (Accessed: 04 January 2017).
[47] 中国钢铁工业年鉴 Chinese Steel Industrial Statistics, 2014.
[48] 中国钢铁协会统计报告 China iron and steel association statistics report, 2014.
[49] 钢铁去产能规划或年后发布 近 20 年最大去产能运动正式登场-华尔街见闻, 30 January 2016. [Online]. Available: http://wallstreetcn.com/node/229511. (Accessed: 05 January 2017).
[50] PBL Netherlands Environmental Assessment Agency, Trends in Global CO2 Emissions: 2015 Report – PBL Netherlands Environmental Assessment Agency, (2015) [Online]. Available: http://www.pbl.nl/en/publications/trends-in-global-co2-emissions-2015-report . (Accessed: 04 January 2017).
[51] 魏晋渝, "中国水泥年鉴 China Cement Almanac, 中国建材工业出版社, March 2015.
[52] 张江涛, 孙玉峰, and 刘寿绵, "《 水泥单位产品能源消耗限额》新国标解读与实施方法," 中国 水泥, and 水泥供给侧改革系列报告之产能篇:水泥产能过剩到底有多严重 - 今日头条 8, 67–71, 2013.
[53] 中 国 网(https://www.toutiao.com/), 吴文坤, "水泥产能过剩逼政策出手 地方政府跑发改委求情," 每日经济新闻, 08 March 2016. [Online]. Available: http://www.toutiao.com/i6259609871537144322/. (Accessed: 05 January 2017).
[54] 国务院办公厅关于促进建材工业稳增长调结构增效益的指导意见, 19 July 2013. [Online]. Available: http://finance.sina.com.cn/chanjing/cyxw/20130709/010716054454.shtml. (Accessed: 05 January 2017).
[55] 董剑, 王迪, 陈施华, and 赵青林, "我国水泥工业产能及能耗现状浅析," 新世纪水泥导报. Guidance on Promoting the Steady Growth and Adjusting the Structure of the Building Material Industry., State Council of the People's Republic of China, 2016.
[56] 水泥行业煤炭消费总量控制方案及政策研究, 2, 1–6, 2016.
[57] 顾阿伦, 史宵鸣, 汪澜, and 赵秀生, The Natural Resources Defense Council (NRDC), 2015.
[58] 中国水泥行业节能减排的潜力与成本分析 中国人口资 源与环境 方晓骅, "我国石油和化学工业节能潜力与技术选择," *第十三届中国科协年会第* 22(8), 16–21, 2012.
[59] *分会场·实现* 2020 *年单位* GDP *二氧化碳排放强度下降* 40–45 *的途径研讨会论文集* 2011.
[60] B. Zhu, W. Zhou, S. Hu, Q. Li, C. Griffy-Brown, Y. Jin, CO_2 emissions and reduction potential in China's chemical industry, Energy 35 (12) (2010) 4663–4670.
[61] 张永华, 杨令 王亭杰, "氮肥行业产能过剩性质分析和应对," 现代化工 6, 7–12, 2015.
[62] 陈宏坤, 田贺永, 肖远牲, and 陈昌照, "我国炼油行业碳排放估算与分析," 油气田环境保护, 22(6), 1–3, 2012.
[63] 2015–2020 年中国化肥市场调查研究及发展前景趋势分析报告," 中国产业调研网, 1506891, 2015.
[64] 原野, "取消核准, 对化肥市场影响几何?," 化工管理, 31, 65–67, 2014.
[65] 关于进一步深化化肥流通体制改革的决定, State Council of the People's Republic of China, 2009.
[66] 温倩 and 李志坚, "氮肥行业' 十三五' 发展规划研究," 氮肥技术 年 05, 1–4, 2015.
[67] 刘化章, "传统合成氨工业转型升级的几点思考," 化工进展, 34, 10, 3509–3520, 2015.
[68] Annual Financial Report of CNPC, (2015).
[69] Annual Financial Report of Sinopec, (2015).
[70] 2015 年中国炼油行业发展趋势," 中国产业信息网, (23 October 2015).
[71] 关于石化和化学工业节能减排的指导意见, Ministry of Industry and Information Technology of the People's Republic of China, 2013.
[72] McKinsey & Company, Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve, (2009) [Online]. Available http://www.mckinsey.com/?/media/McKinsey/Business%20Functions/Sustainability%20and%20Resource%20Productivity/Our%20Insights/Pathways%20to%20a%20low%20carbon%20economy/Pathways%20to%20a%20low%20carbon%20economy.ashx.
[73] 国家重点节能低碳技术推广目录（2015 年本 节能部分）," 国家发改委 (NDRC), 2015.
[74] 中国统计年鉴 China Statistical Yearbook, 2014.
[75] 国务院发展研究中心产业经济研究部, 中国汽车产业发展报告. 社会科学文献出版社, 2010.
[76] 节能与新能源汽车产业发展规划(2012—2020 年), State Council of the People's Republic of China, 2012.
[77] Building Energy Use in China, Transforming Construction and Influencing Consumption to 2050, IEA Tsinghua University, 2015.
[78] 清华大学建筑节能研究中心*中国建筑节能年度发展研究报告* 2014 中国建筑工业出版社 2014.
[79] IEA, Energy Technology Perspectives 2015, (2015).

[80] 唐晓灵 and 白宝焕, “我国房地产开发市场集中度研究,” 商业时代 26, 126–128, 2012.
[81] 李佐军 and 赵西君, “我国建筑节能减排的难点与对策,” 江淮论坛 2, p. 1, 2014.
[82] 住房城乡建设部办公厅关于 2013 年全国住房城乡建设领域节能减排专项监督检查建筑节能检 查情况的通报 MHURD of the People’s Republic of China, 2013.
[83] 关于 2010 年全国住房城乡建设领域节能减排专项监督检查建筑节能检查情况通报 MHURD of the People’s Republic of China, 2010.
[84] 毛义华 and 蔡临申, “我国建筑节能的现状及其对策分析,” 技术经济与管理研究 1, 58–59, 2007.
[85] IEA, Technology Roadmap: Energy Efficient Building Envelopes, (2013) [Online]. Available: https://www.iea.org/publications/freepublications/publication/technology-roadmap-energy-efficient-building-envelopes.html . (Accessed: 04 January 2017).
[86] 科学生活：‘一表一阀’能否实现供暖节能？,” 科技日报, 15 April 2008. [Online]. Available: http://www.gov.cn/fwxx/kp/2008-04/15/content_944877.htm. (Accessed: 04 January 2017).
[87] M. Forsythe, China Aims to Spend at Least $360 Billion on Renewable Energy by 2020, The New York Times, 2017 [Online]. Available: http://www.nytimes.com/2017/01/05/world/asia/china-renewable-energy-investment.html . (Accessed: 06 January 2017).
[88] B. Naughton, K.S. Tsai (Eds.), State Capitalism, Institutional Adaptation, and the Chinese Miracle, Cambridge University Press, New York, NY, 2015.
[89] Bloomberg News, China Picking Winners in Solar Industry With Backing for Yingli, Bloomberg.com, 2016 [Online]. Available: https://www.bloomberg.com/news/articles/2016-02-26/china-picking-winners-in-solar-industry-with-backing-for-yingli . (Accessed: 06 January 2017).